Towards a methodology to define safety criteria for CO_2 geological storage

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Abstract

While CO_2 geological storage is now broadly recognized as one credible option to mitigate climate change, its safety with respect to human health and the environment has to be demonstrated before starting industrial-scale operations. This is why BRGM has launched a research project dedicated to safety criteria for CO_2 geological storage. Such criteria can be defined as requirements to ensure near-zero impacts on persons, goods and the environment, in the short, middle and long term.
A review of the risk assessment literature reveals that many studies deal with CO_2 leakages considering the effectiveness of atmospheric emissions reduction. Fewer concentrate on potential health, safety and environmental impacts. Our approach aims to base the definition of safety criteria on the human and environmental targets at risk, like for industrial pollution risk management. Our work focuses on the underground part of the storage, since a classical industrial risk analysis is relevant for surface facilities.
Current regulations and the state of the art of industrial analogues, like underground natural gas storage or radioactive waste deep disposal, do not appear very prescriptive. However, some methods may be usefully transposed to CO_2 storage.
Generic safety criteria for CO_2 storage cannot be determined, because of the variability of possible storage sites. Hence, we started our work on a scenario-based method allowing the handling of site specificity in the elaboration of criteria. A first attempt in constructing risk scenarios uses the Features, Events, Processes database. In later steps we will consider alternative methods and implement our own methodology.

Introduction

CO_2 capture and storage has been validated by the IPCC (2005) as part of a portfolio of measures to mitigate climate change. With the perspective of a near deployment, concern shifts from a strict performance point of view to a safety approach. Like for any other industrial activity, it is necessary to guarantee the absence of adverse effects on health, safety and the environment because of CO_2 capture and storage facilities. This appears as a prerequisite for industrial-scale storage operations.
If CO_2 capture does not need new conceptual developments for safety assessment given the experience of industrial risk evaluation, demonstrating safety of CO_2 underground injection raises challenges, mainly due to the time scales involved and to uncertainties related to the geological medium. Therefore, BRGM has launched a research project dedicated to safety criteria for CO_2 geological storage, which should enable to assess safety for individual projects.
This paper presents the advancement of this work. In a first part, the need for safety criteria is justified and the specific obstacles to their setting underlined. Then we detail our approach. Begun by a review of the safety principles for underground storage analogues, it is based on the elaboration of scenarios, which should be confronted to human and environmental elements at risk for inferring safety criteria. The foreseen continuation of this research is presented next, along with the key questions that it raises. Ultimately, first conclusions relative to safety criteria are drawn under the form of a general preliminary list.

The need for safety criteria for CO_2 geological storage

Most of the research undertaken so far with regard to leakage assessment from CO_2 geological storage sites was directed toward a performance evaluation, especially works relative to the Weyburn or Sleipner pilots (see for example Zhou *et al.* [2005], Lindeberg and Bergmo [2003]). Calculations usually dealt with annual leakage rates, expressed as fractions of the stored mass, with the proportion of CO_2 remaining in the reservoir, or with the retention time. This was justified by the need to check CO_2 geological storage ability to mitigate climate change, which required a sound estimate of its performance. In that view, when validating this technology as part of a portfolio of measures to mitigate climate change, the IPCC (2005) set as an objective for storage projects a retention time of 1000 years for most of the stored gas, which corresponds to a release rate smaller than 10^{-3} of the CO_2 in place per year. However, this value, as well as other ones found in such performance assessment works, is not related to risks induced locally to Health, Safety and the Environment (HSE) in case of a leakage from a CO_2 storage site. Therefore, it is not relevant for assessing safety for such a site.
Now, like for any other industrial activity, safety must be guaranteed before launching industrial-scale operations. That is to say that they shall not be harmful to human health, goods and the environment;

at least their deleterious effects should not exceed the benefits they bring. Possible HSE risks of a storage site have then to be considered in the design and implementation of a project. This requires assessing the effects of leaks as well as of other undesired phenomena caused by CO_2 injection, namely risks due to underground geomechanical disruption. By the way, containment criteria determined when considering local risks may differ significantly from the performance objectives to mitigate climate change (Pearce *et al.* [2005]).

Safety criteria appear therefore necessary to enable an evaluation of the risks generated by a project, and also to support communication about risks. They can be defined as **requirements to ensure near-zero impacts on health, safety and the environment, in the short, middle and long term**. Setting such criteria would give a means to evaluate in a relatively quick manner whether safety of a storage system is appropriate. As such, it would be helpful to an administration or a control institution, as well as to storage operators whose project design would integrate these criteria.

Specific difficulties to define safety criteria

Risks caused by surface facilities involved in CO_2 geological storage do not show any originality in comparison to existing industrial activities. CO_2 is a fairly common product in various industries, used for example as a food additive, fire extinguisher, cooler, for chemical compounds synthesis or water treatment (INRS [2005]). Moreover, the transport and injection technologies enter the frame of competencies from oil and gas industries, which have gained experience for decades in handling CO_2 through Enhanced Oil Recovery (EOR) operations. Consequently, no innovation is needed to assess safety for surface facilities of CO_2 storage sites.

On the contrary, what makes this technology specific with regard to safety analyses is its underground part. This is firstly due to the time scales involved: if CO_2 is to remain stored for hundreds of years, then HSE risks related to CO_2 releases need to be assessed on the short term as well as on the very long term, which constitutes a rather unusual exercise. Secondly, this long-term evolution is influenced by multiple coupled phenomena. Past and current research dedicated to CO_2 geological storage all around the globe aims to improve our understanding of the various hydrogeological, geochemical, thermal or geomechanical processes. Nevertheless, this very complex system will remain incompletely known. The geological medium itself cannot be comprehensively characterized, so that significant uncertainties surround evolution models and computations. Uncertainties about geological parameters relate to both their variability and imprecision due to our only partial knowledge.

Local risks are highly dependent of the site, not only because of the variety of geological media. The local configuration at surface, in terms of topography, meteorological conditions and presence of vulnerable elements, plays a determining part for the consequences of potential releases. Therefore, safety of CO_2 geological storage cannot be assessed in a generic way, but it needs to be adapted on a case-by-case basis (Pearce *et al.* [2005]). Generic safety criteria cannot be defined; their determination must take account of the specificities of each site.

Research undertaken at BRGM with regard to safety

BRGM launched in 2006 a project aiming at defining safety criteria for CO_2 geological storage. Given what has been described above about the specificities of this case, our study is devoted to the underground part of the storage system.

Risks related to CO_2 storage come from eventualities of:

- CO_2 release in surface affecting human health or the environment;
- CO_2 or acidified brine migrating from the reservoir to freshwater aquifers, which could make their water improper for consumption or any other use;
- Uplift, subsidence or seismic events triggered by the geomechanical disruption of the underground which can induce ground deformations at surface or even destructive ground shaking.

Work inside BRGM project dedicated to safety has focused on leakage risks, with their time scales particularities.

Investigations about safety approaches for industrial analogues

Our work has begun by a review of the safety principles, practices and regulation for other forms of underground storage, that is to say natural gas seasonal storage and radioactive waste deep disposal. These activities show large differences with CO_2 geological storage in terms of time scales, processes involved or risk induced; but we thought interesting to investigate how the specificity of the geological medium was handled. The focus has been made on the French case, in particular concerning the regulation. Since no radioactive waste deep disposal is in place, our study has looked at the measures framing research on that topic and at the principles for safety assessments of such disposals.

The French regulation relative to natural gas temporary storage is fairly precise in terms of licensing process and required documents. However, it does not appear very prescriptive for safety: no criteria are established *a priori*; the operator is responsible for the safety demonstration, which is then controlled by the administration. Examining the licensing demand for one particular storage site and reviewing accidents reports (IEA GHG [2006]) from this sector revealed that safety concerns are mainly focused on industrial facilities. Unlike in the case of CO_2, natural gas storage does not have to consider long term, and reversibility is intrinsic to the technology. This probably justifies that no safety criteria regarding the underground apply to these operations.
The basic principle for protection of persons and the environment when operating radioactive waste deep disposal is to limit the radiological impact to a level "As Low As Reasonably Achievable" (ALARA concept). This framework looks instructive in its principles for assessing safety in the long-term. Safety is evaluated on the basis of individual annual exposure, for which a threshold (0.25 mSv/yr) is set. A conservative approach or an explicit treatment of uncertainties is required. Ultimately, the assessment must rely on the distinction between a reference situation and hypothetical scenarios. Although CO_2 geological storage presents significant differences compared to radioactive waste deep disposal, especially in terms of risk, similar principles may be adopted by the methodology to assess long-term safety. In particular, reference and alternative scenarios may be constructed by adapting the proposed list to the case of CO_2 or establishing a similar list.

Construction of leakage scenarios
Indeed, such an approach based on evolution scenarios for assessing long-term safety seems relevant to the multiplicity of phenomena involved and to site variability: elaborating scenarios for describing a site's future enables to take account of its specificities. Therefore, to test how this can be done, first attempts have been made to construct long-term scenarios for CO_2 geological storage. For that, we chose to consider a model of CO_2 storage in aquifer in the Paris Basin. This does not correspond to a storage project in progress, but we used rather generic characterization data resulting from investigations for that option (see in particular Fabriol *et al.* [2006]).
We examined how to use the online CO_2 Features, Events, Processes (FEP) database by Quintessa (http://www.quintessa-online.com/co2/) in this scenario construction process. We were partially guided by the use that had been made of the TNO FEP database during the CO2STORE project (Svensson *et al.* [2005]). However, this application has appeared to us rather tedious and insufficiently efficient. It seems more relevant to see the FEP database as an audit tool, which is by the way the use recommended by the producers of the Quintessa database (Savage *et al.* [2004]). Consequently, further work is needed to find what could be the best method to elaborate scenarios.

Nevertheless, we identified a set of six leakage scenarios in the case of CO_2 storage in a deep aquifer in the Paris Basin. These scenarios, represented on figure 1, are:

- Leakage consecutive to the degradation of a well;
- Leakage due to the fracturing of the cap rock because of the overpressure;
- Leakage through the pore system of the cap rock, due to an overpressure or to the presence of an undetected zone of higher permeability;
- Leakage through an existing fault;
- Migration of formation water, acidified or not, from the reservoir to freshwater aquifers;
- Leakage through an intentionally or involuntary created open hole: abandoned wells, future drilling in the reservoir, malicious act on a well or any other human intrusion.

Moreover, four variants were found susceptible of altering these scenarios:

- Geochemical changes due to CO_2 injection;
- Presence of impurities in the injected CO_2 stream;
- Mobilization of co-contaminants in the reservoir;
- Changes in hydrogeological boundary conditions due to climate or geological changes.

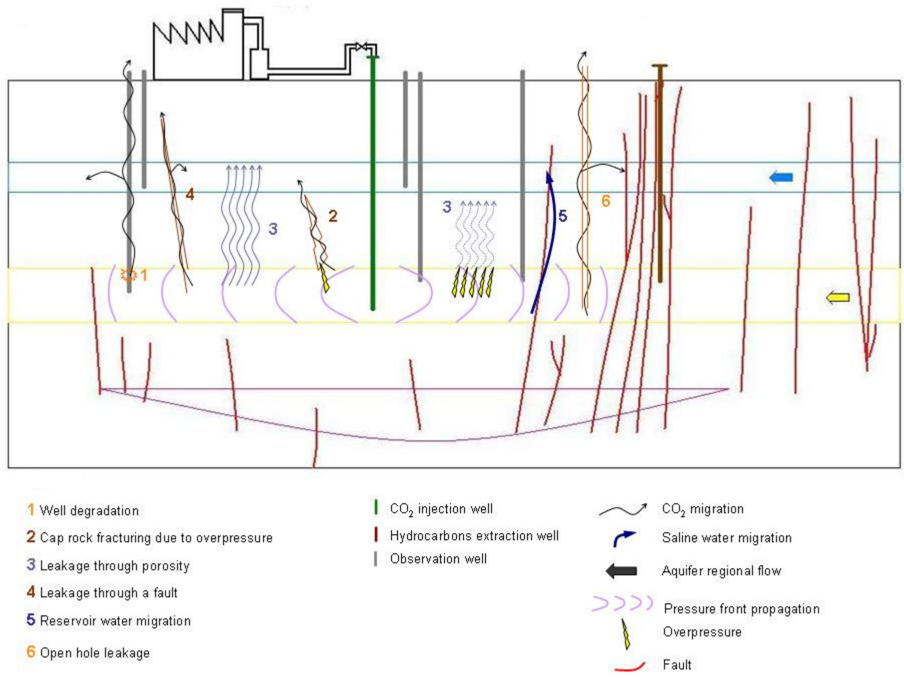

Figure 1 - Leakage scenarios for CO_2 storage in an aquifer in the Paris Basin

Safety criteria have to be based on environmental and human elements at risk

Classically, an assessment of industrial risk, either chronic or accidental, looks at the possible impacts of feared phenomena to evaluate their acceptability. Risk is defined as the combination of the hazard and the vulnerability of targets. In our view, determining safety criteria for CO_2 geological storage must rely on a similar approach focused on the potentially exposed elements. In other words, a CO_2 release without significant consequences should be acceptable (provided it still meets the performance requirements to mitigate climate change). In an ideal site where there would be neither human beings nor any environmental stakes, CO_2 leaks should not be a worry from the HSE point of view.

As a consequence, key points are the identification of the elements that could be at risk and of their potential mode and level of exposure. This needs to be done in the particular configuration of each storage site. Describing the various elements potentially affected should be one of the first steps of the assessment. The targets to consider are humans and their goods, environmental stakes in both surface and deep ecosystems, and freshwater aquifers or other resources in the overburden that need to be protected. A site model must then represent the storage system along with the elements that must not be endangered. In our case, considering typical surface conditions and land use for the Paris Basin, we drew a schema of a site of storage in aquifer figuring the targets, as shown in figure 2.

Safety criteria must then be inferred from the verification that the identified targets are not jeopardized, *i.e.* that their exposure remains at an acceptable level. The leakage scenarios indicate the migration pathways from the source of hazard to the targets; thus the modes of exposure of the various vulnerable elements in each of these hypothetical situations are known. Modeling those scenarios will provide the level of their exposure, as a function of a number of parameters. Comparing this exposure to a threshold dependent on the type of target should enable the setting of criteria.

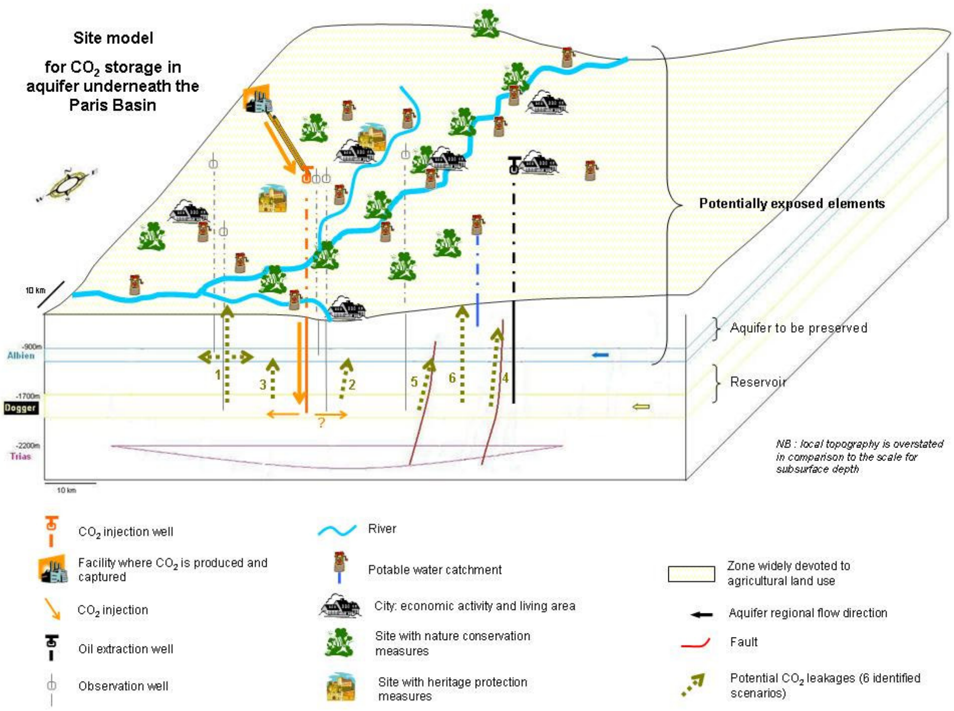

Figure 2 - Site model for a storage site in an aquifer of the Paris Basin

Key questions & further work

This approach of safety criteria determined according to the potential targets at risk requires a focus on their exposure to the hazard. The transfer of CO_2 towards these exposed elements must therefore be carefully addressed. Modeling the leakage scenarios will provide the quantification of this transfer. Feasibility and easiness of this modeling will be critical for applicability of our method.

Moreover, danger does not only come from CO_2, but also from associated impurities. Their fate as well as their influence on the leakage process should be investigated further.

Our criteria should be derived from exposure thresholds. Determining such values in surface for human beings should be relatively easy, since occupational exposure limits exist in the USA for example. It may be more complex for environmental compartments, since the response of species and ecosystems is still poorly known, or for freshwater aquifers.

Crucial is also the choice of time and space scales. Consistently with the time frame adopted by the IPCC, the value of 1000 years will be our guide, bearing in mind that this value results from climate change mitigation aspects. The space scale is problematic: currently we have few elements to appreciate the area in which targets have to be identified and characterized in order to assess risk. Once again, a generic answer can probably not be given to that question. The domain of interest will probably be determined after first simulations have given an order of magnitude for the extension of the CO_2 bubble over the assessment period. For instance, simulations for Sleipner found that the CO_2 plume would be contained in a 70 km² zone (Lindeberg and Bergmo [2003]). But this depends widely on site properties, especially on reservoir thickness.

Earlier was highlighted the importance of uncertainties, due to variability and to an incomplete knowledge of the geological medium. Dedicated tasks are needed to represent the data, uncertainties and propagation of these uncertainties throughout a calculation workflow, in order to evaluate the accuracy and reliability of our computations. In further work, we propose to use the principles of fuzzy logic to perform these tasks.

The whole of the research presented here about safety criteria and the methodology to define them is being continued at BRGM, especially in a dedicated joint project[1], entitled CRISCO2, partially funded by the French National Agency for Research (ANR). The aim is the implementation of a simple methodology to define safety criteria, relying on scenarios and based on the identification of elements to be protected. As written above, uncertainties will be handled. In addition to the

[1] In that project BRGM is collaborating with teams from: TOTAL; Armines; IRIT, University Paul Sabatier, Toulouse; Centre of Hydrogeology , University of Neuchâtel (Switzerland).

methodology, this project should deliver realistic safety criteria for CO_2 storage in aquifer as well as in depleted oil field.

A first list of safety criteria

For now, we have gathered a first list of generic criteria on the basis of our review of industrial analogues practices and of the leakage scenarios identified. This work needs to be completed and refined. The criteria relate to five essential concerns:

- CO_2 containment;
- Reservoir conservation, which includes cap rock integrity;
- Well integrity;
- Gas quality, *i.e.* purity of the CO_2 stream and presence of other substances;
- Groundwater protection.

Achieving these objectives imposes to meet requirements relative to:

- The necessary knowledge of the storage system, before and during the operations:
  - Geological and hydrogeological characterization;
  - Mechanical properties of the reservoir;
  - Cap rock properties, especially mechanical and petrophysical properties;
- The control of operating parameters:
  - Injection pressure and rate;
  - Injected volume;
  - Composition of the injected gas;
  - Monitoring plan;
- The monitoring of essential data:
  - Horizontal and vertical extent of the CO_2 plume;
  - Groundwater quality;
  - Well integrity;
- The planning of remediation measures, including reversibility as an extreme solution, during the operational phase and for an ulterior period to be defined.

Conclusion

Principles of a methodology to define safety criteria for CO_2 geological storage have been set. Such criteria must be adapted to the specificities of each site. Hence, to deal with site variability, the method will rely on the elaboration of long-term scenarios, which should describe more or less plausible evolutions of the storage for1000 years. The determination of safety criteria must be based on the identification of the human and environmental elements that could potentially be exposed. For that, their modes and level of exposure over the various leakage scenarios have to be assessed. Criteria will be expressed that guarantee keeping this exposure within an acceptable range.
Now that these principles are set, this work will be continued to improve the way to construct scenarios, to evaluate the transfer of CO_2 toward the targets, and generally to make this method applicable. A number of questions remain to be addressed. Nevertheless, a preliminary list of criteria has been presented, which should be seen as a support for further research and needs to be specified and completed.

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